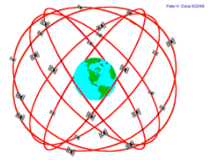

An Experimental Kalman Filter Approach to the International Terrestrial Reference Frame Realization

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Current ITRF Status and Rationale

- **Secular frame characterized by X, V and a full covariance matrix**
  - Linear motion models for all sites
  - Origin at mean but not instantaneous CM
    - CM for secular motion
    - Close to CF for sub-secular motions
  - The linear motion model works very well and the ITRF2008 frame is quite stable at 0.3 – 0.5 mm/yr
- **The case for an Experimental Kalman Filter Approach**
  - Non-linear motion, sites with short data span
  - Near real-time orbit determination and global monitoring
  - Unify different geodetic data time series in one and the same frame
  - Origin at nearly instantaneous CM

Experimental Kalman Filter Approach to TRF

- **One reference frame realized by time series**
- **Origin defined at weekly (nearly instantaneous) CM**
  - Currently through SLR data
  - Could take other data or models in the future
- **Scale realized by weekly SLR/VLBI data**
- **Orientation defined weekly by convention and no net rotation**
- **Local ties are applied only once in the weeks of surveying or within the continuous segments without offsets**
- **Co-motion constraints are applied to most if not all co-located sites**

Weekly Combination Strategy

- **Use CATREF heritage**
- **Combination done at weekly basis**
- **Kalman Filter Data Update**

- Coordinates in file k

$$X_s^i = X_c^i + (t_s^i - t_0)\dot{X}_c^i + T_k + D_k X_c^i + R_k X_c^i$$

$$+(t_s^i - t_k)[\dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i]$$

- Local Ties applied once

- Tight Orientation Constraints every week

$$\mathbf{0 = B(X_c - X_r)}$$

- Weekly displacements at most co-located sites are constrained to be the same

EOP in file k

$$x_s^p = x_c^p + R2_k$$
$$y_s^p = y_c^p + R1_k$$
$$UT_s = UT_c - \frac{1}{f} R3_k$$
$$\dot{x}_s^p = \dot{x}_c^p$$
$$\dot{y}_s^p = \dot{y}_c^p$$
$$LOD_s = LOD_c$$

Time Update or Prediction

- **Coordinate Decomposition**

$$\mathbf{X}_c = \begin{pmatrix} X_c^1 \\ Y_c^1 \\ Z_c^1 \\ . \\ X_c^i \\ . \end{pmatrix} = \mathbf{X} + \mathbf{S_p}$$

- **Equation of Dynamics**
- **Time Update or State Transition**

$$\begin{bmatrix} X_k \\ V_k \\ S_k^{next} \\ S_k^{now} \end{bmatrix} = \begin{bmatrix} 1 & dt & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 2e^{-dt/\tau}\cos 2\pi \dfrac{dt}{T} & -e^{-2dt/\tau} \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X_{k-1} \\ V_{k-1} \\ S_{k-1}^{next} \\ S_{k-1}^{now} \end{bmatrix} + \begin{bmatrix} \varepsilon_x \\ \varepsilon_v \\ \varepsilon_p \\ 0 \end{bmatrix}$$

$$\mathrm{EOP}_k = \mathrm{EOP}_{k\text{-}1} + \varepsilon_{\mathrm{EOP}}$$

$$\mathrm{T}_k = \mathrm{T}_{k\text{-}1} + \varepsilon_{\mathrm{T}}$$

EGU2012-11920 XL74
Abbondanza et al.

Flow Chart of Weekly Combination Filter-Smoother

Pre-processing
- SLR/VLBI/GPS/DORIS: neqloose, proj, stack_clean
- Tie, breaks, vcon., Datum
- Weekly input files: OPT, TSG, Datum

Input Control parameters

Bookkeeping
- Sites, ERP, TSG
- Segments, POSB, VELB, Tie epoch, Co-motion pairs

LSQ Weekly Combination
- Meter level a priori + 1 m ties
- Origin from weekly SLR CM
- Scale from weekly VLBI/SLR
- Cooperating realistic ties

Nominal Weekly X, ERP, TSG

Non-cooperating realistic ties

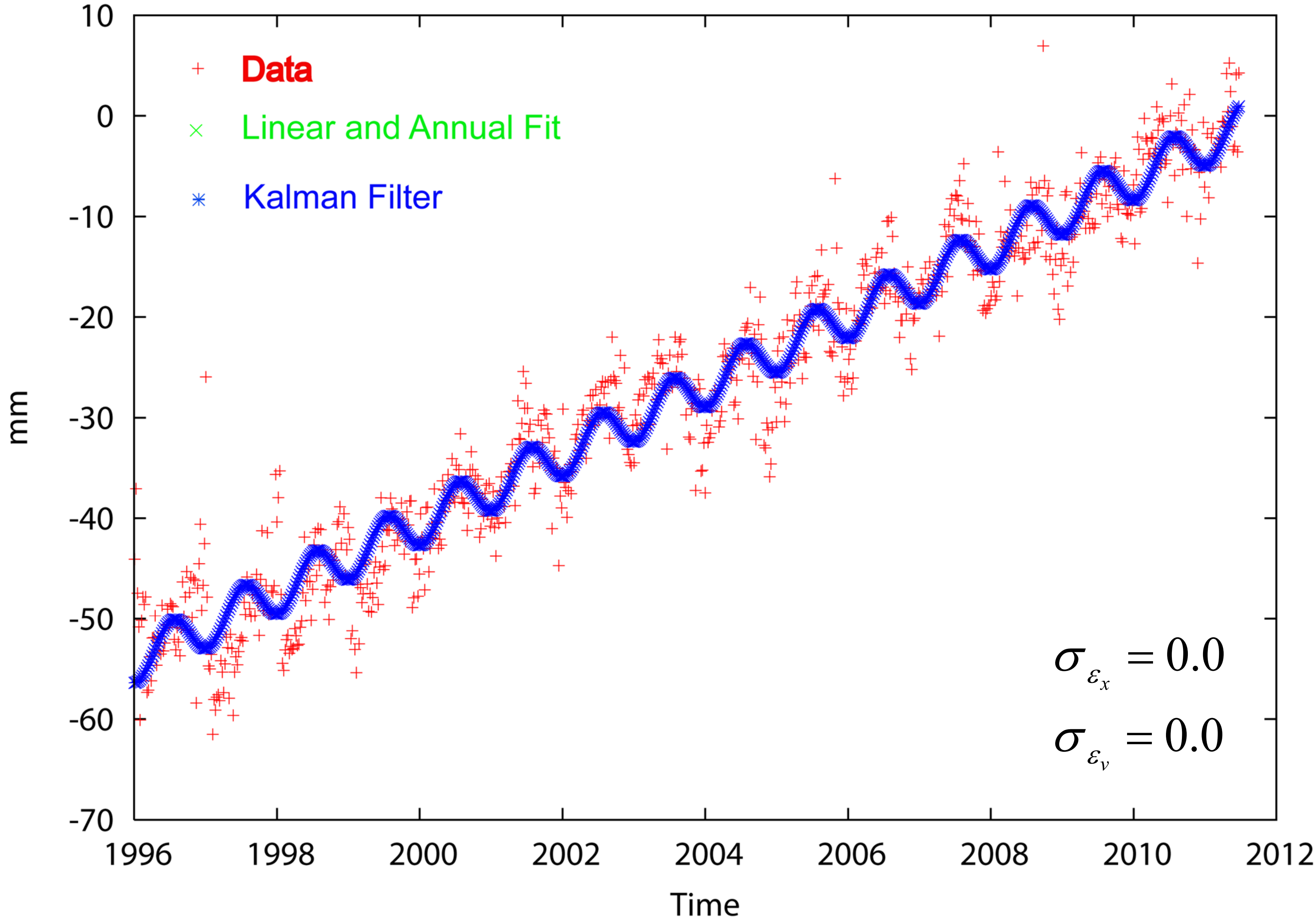
Tight orientation/co-motion constraints

Dynamics/A priori Stochastic σ_ε

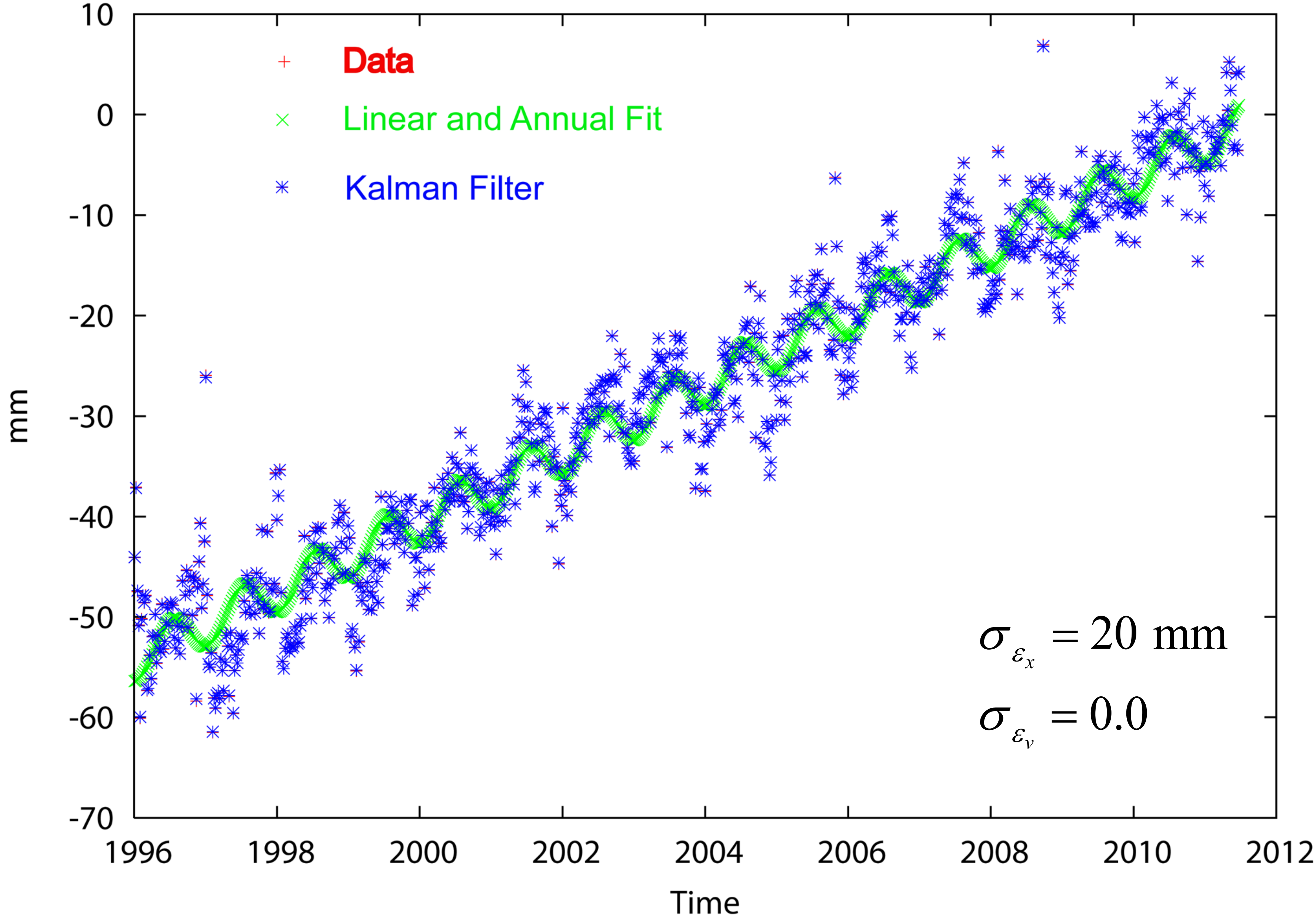
Kalman (Forward) Filter Data update/Time update(Backward) Smoother

Weekly coordinates, residuals/statistics

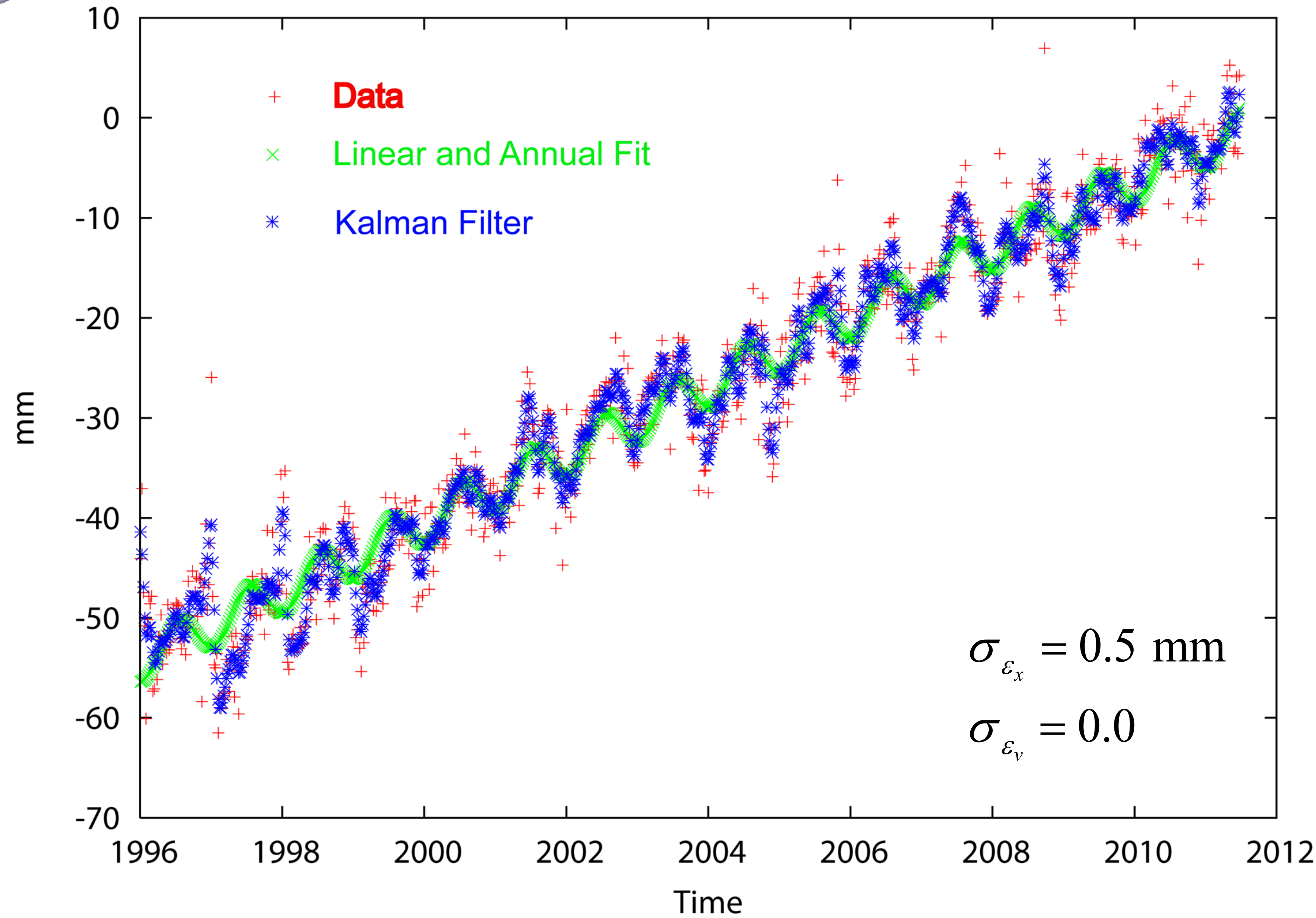
Kalman Filter and RTS Smoother



Kalman Filter and RTS Smoother



Kalman Filter and RTS Smoother



Transformation Parameters between ITRF2005 and Weekly Combination (1996-2005

No Annual Components

Tx (mm)	Ty (mm)	Tz (mm)	D (ppb)	Rx (µas)	Ry (µas)	Rz (µas)
0.1	-0.1	-0.4	-0.69	-26	-1	11
Vx (mm/y)	Vy (mm/y)	Vz (mm/y)	(ppb/y)	$\dot{R}_x$ (µas/y)	$\dot{R}_y$ (µas/y)	$\dot{R}_z$ (µas/y)
0.0	0.0	0.3	0.00	10	-5	3

With Annual Components

Tx (mm)	Ty (mm)	Tz (mm)	D (ppb)	Rx (µas)	Ry (µas)	Rz (µas)
0.1	0.1	-0.4	-0.65	-26	-2	11
Vx (mm/y)	Vy (mm/y)	Vz (mm/y)	(ppb/y)	$\dot{R}_x$ (µas/y)	$\dot{R}_y$ (µas/y)	$\dot{R}_z$ (µas/y)
0.0	0.0	0.2	-0.01	10	-5	3

Summary

- Consistently and accurately defined and realized TRF is essential for global change monitoring
- Experimental TRF realized by nearly instantaneous geocentric time series and combinations are done weekly
- The Kalman filter and RTS smoother offer great power and flexibility to estimate time-dependent parameters. Easy on constraints over variables such as displacements
- Fragmented time series at co-located sites are unified dynamically
- Time series from different geodetic techniques are unified in the same frame